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13. ABSTRACT *(Maximum 200 words)*
The U.S. and Canadian weather services use heat indices as the basis for issuing warnings for a significant hazard of heat injury. However, the U.S. and Canadian indices differ. The U.S. uses the Heat Index (HI) based on Steadman's model. Canada uses Humidex (HD). Our comparison used the USARIEM Heat Strain Decision Aid (HSDA) to evaluate both indices. We ran the HSDA model with the inputs used to generate HI. The study is limited to data for HI £ 135°F. HSDA calculates rectal temperature (Tre) which was plotted against HI and HD. For HI, the relationships were linear. For HD the relationships were curvilinear. When R2 values for HI and HD were compared, there was no difference. Our preference is for HD as it uses dew-point temperature rather than relative humidity and directly represents the physical interactions of temperature and humidity, whereas HI is derived in a more circuitous manner. Both indices are validated by the statistical relationship between HI or HD and the HSDA calculated Tre. However, as indices vary only weather inputs, thermal indices are less versatile than more complex models that incorporate variation in activities

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USARIEM TECHNICAL REPORT T03-17

EVALUATION OF WEATHER SERVICE HEAT INDICES USING THE USARIEM HEAT STRAIN DECISION AID (HSDA) MODEL

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BACKGROUND

Current U.S. Army doctrine uses Wet Bulb Globe Temperature (WBGT) to determine when environmental conditions present a significant risk of heat injury. WBGT is used by the military and industry, but the requisite meteorological data are not readily available to the civilian population. The U.S. and Canadian weather services provide alternative heat indices based on air temperature and humidity. These civilian indices are more readily available through radio and television media outlets, and may be of value to supplement WBGT, or provide an alternative estimate of the heat hazard when WBGT values are not available. This study addresses the validity of civilian indices as predictors of the risk of heat injury.

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EXECUTIVE SUMMARY

Climatic or thermal indices that relate environmental conditions to the potential hazards of exposure to thermal stress are important to civilian, industrial and military populations. Ideally, indices are relatively easy to derive from basic weather inputs and usually provide the user with relatively simple guidance for determining when a thermal hazard exists. The U.S. and Canadian weather services use heat indices as the basis for issuing warnings when meteorological conditions present a potential significant hazard of heat injury. However, the U.S. and Canadian indices differ. The U.S. uses the Heat Index (HI) based on a regression derived from a model by Steadman (24). The Canadian index is Humidex (HD), developed by Lally and Watson (11) and refined by Masterton and Richardson (12). The Joint Action Group for Thermal Indices (JAG/TI) of the Office of the Federal Coordinator for Meteorological Services and Supporting research (OFCM) is attempting to compare the 2 indices, with an ultimate objective of sharing a common index (5).

One approach for comparing the 2 indices is to use another model to evaluate the indices. The USARIEM Heat Strain Decision Aid (HSDA (2,22)) which was developed for young, fit military populations, calculates rectal temperatures (T_{re}) for a given set of inputs including air temperature (T_a), humidity, wind speed, mean radiant temperature (T_{mrt}), clothing, activity level, height and weight. The Steadman model requires specific inputs for height (170 cm), weight (67 kg), activity level (walking at 1.34 $m{\cdot}s^{-1}$, 320 W), clothing (1.3 clo), wind speed (2.5 $m{\cdot}s^{-1}$), and no solar radiation (shade). Some inputs, such as clothing, can only be approximated for the HSDA. We ran the HSDA model for the range of conditions identified by the NWS as appropriate to HI ($HI \leq 135°F$, RH=30 to 100%, Ta=26.7° to 45°C). An important caveat is that the study is limited to data for $HI \leq 135°F$. We calculated HD for the same combinations of temperature and humidity, thus we had values for both HI and HD matched to the HSDA estimates of T_{re}. We repeated the calculations with a T_{mrt} that approximated the maximum radiant load, based on the work of Matthew et al. (14). We then plotted the calculated T_{re} against both HI and HD.

For HI, the relationships with the HSDA estimates of T_{re} were linear, whereas for HD, the relationships were curvilinear or exponential. For the HI linear regressions, correlation coefficient (R^2) values ranged from 0.95 to 0.99. For the exponential HD equations, R^2 values ranged from 0.90 to 0.94. To improve the fit for the HD predictions, we derived second order polynomial equations for the relationship between HD and the predicted T_{re}. When the R^2 values were compared for the HI and HD equations, the values were quite similar. R^2 values were 0.98-0.99 for STANDARD and 0.96-0.98 for SUN. Our preference is for HD, as it uses T_{dp} rather than RH, and it is a direct representation of the physical interactions of temperature and humidity, whereas HI is derived in a more circuitous manner using Steadman's original model.

Both indices are validated by the close statistical relationship between HI or HD and the HSDA calculated T_{re}. Bioclimatic indices hold physiological values constant while varying only weather inputs. More complex models, such as HSDA, incorporate

variation in activities and clothing as well as the weather inputs. Consequently, the complex models are more versatile.

INTRODUCTION

The Joint Action Group for Thermal Indices (JAG/TI) of the Office of the Federal Coordinator for Meteorological Services and Supporting research (OFCM) was tasked with evaluating the heat and cold thermal indices used by the NWS and MSC. The two weather services use different thermal indices for both wind-chill and heat exposure. As a result of the work of the JAG/TI, a new WCT was adopted by the U.S. and Canadian weather services for the winter of 2001-2002 (20). At present, the International Society of Biometeorology Commission 6 (ISB C6) is evaluating 3 sets of heat balance models to develop a Universal Thermal Climate Index (UTCI) as an international standard. As the UTCI is intended to replace both current weather service heat indices, rather than developing a new index for heat exposure, both countries may adopt a common heat index as an interim measure (5).

Both heat indices are basically temperature-humidity indices. The heat index (HI) used by the U.S. NWS, was derived from a database generated with a more complex mathematical model developed by Steadman (24). By simplifying a complex, multi-input model into a single, 8-element equation using two common meteorological values, a considerable savings in computing time was accomplished. A similar approach of reducing a complex model to a simple algorithm was used to generate the new WCT (20). The weather inputs for HI are T_a and RH. The equation for HI (17,18, 22) is:

$$HI = -42.379 + 2.04901523 \cdot T_F + 10.14333127 \cdot RH - 0.22475541 \cdot T_F \cdot RH - 6.83783E\text{-}3 \cdot T_F^2 - 5.481717E\text{-}2 \cdot RH^2 + 1.2874E\text{-}3 \cdot T_F^2 \cdot RH + 8.5282E\text{-}4 \cdot T_F \cdot RH^2 - 1.99E\text{-}6 \cdot T_F^2 \cdot RH^2$$

The units for HI are °F. T_F is T_a in units of °F. In addition, a correction factor is sometimes subtracted from HI when RH<13% and T_F is between 80°F and 112°F (19). The adjustment factor was used in this study. Critical values for HI are possible fatigue with prolonged activity starting at HI=80°F; possible heat injury ("sunstroke", heat cramps and heat exhaustion) at 90°F-105°F; the same injuries are likely between 105°-130°F with possible heat stroke; and heat stroke is highly likely when HI≥130°F (17).

The Canadian index used by the MSC is HD. The origins of HD are not particularly well documented. Lally and Watson (11) indicate HD was derived from an earlier work by ASHRAE, but there is no specific reference. The present version of HD is described by Masterton and Richardson (12). The inputs for HD are T_a and dew-point temperature (T_{dp}). Based on Masterton and Richardson, HD≤29°C is considered comfortable. Discomfort starts at a HD of 30°C, and most people should be uncomfortable when HD reaches 40°C. When HD≥46°C, some activity restrictions may be implemented. The equation for HD (12) is:

$$HD = T_a + h$$

$$h = 0.5555 \cdot (e-10)$$

$$e = 6.11^{[5417.753 \cdot (273.16^{-1} - T_d^{-1})]} \qquad [T_d = T_{dp} + 273.16]$$

Although both indices therefore use a combination of temperature and humidity, RH is a derived weather input that requires T_a to calculate and interpret the value, whereas T_{dp} can be measured directly with a weather instrument. Thus, there is a scientific bias towards using T_{dp} to measure humidity.

The issue then becomes a question of which existing North American thermal index is better suited for adoption by both countries. One solution is to do an epidemiological study comparing the prediction of a heat hazard to the actual incidence of heat injury. Unfortunately, assembling an adequate database with both meteorological data and heat casualty records is not a simple task. One potential problem is that if a prevention program utilizing a particular heat index is successful, the greatest correlation will exist with outliers. When people are aware of the hazard, preventative action is more likely. Another problem is the quality of the data. Medical records generally work forward from the entry of the injured party to treatment and recovery or termination, rather than backward to the underlying etiology. The records thus present some difficulty in working backward to determine the weather conditions at the time of injury.

Given that an epidemiological approach is not readily accessible, an alternative method for assessing the two heat indices was needed. The approach used in this study was to use an existing complex heat strain model to predict the incidence of injury, and compare those predictions to the limits set by the heat indices. It would be circular logic to use Steadman's models to validate an equation derived from his model. However, other validated models, which predict core temperature and maximum exposure time, could be compared to the guidance provided by HI. The model used in this paper is a spread-sheet derivative of the HSDA model (2, 23). The HSDA model targets relatively young, fit military populations. Inputs for the model include individual or population descriptors, metabolic rates for activities, clothing, and meteorological conditions.

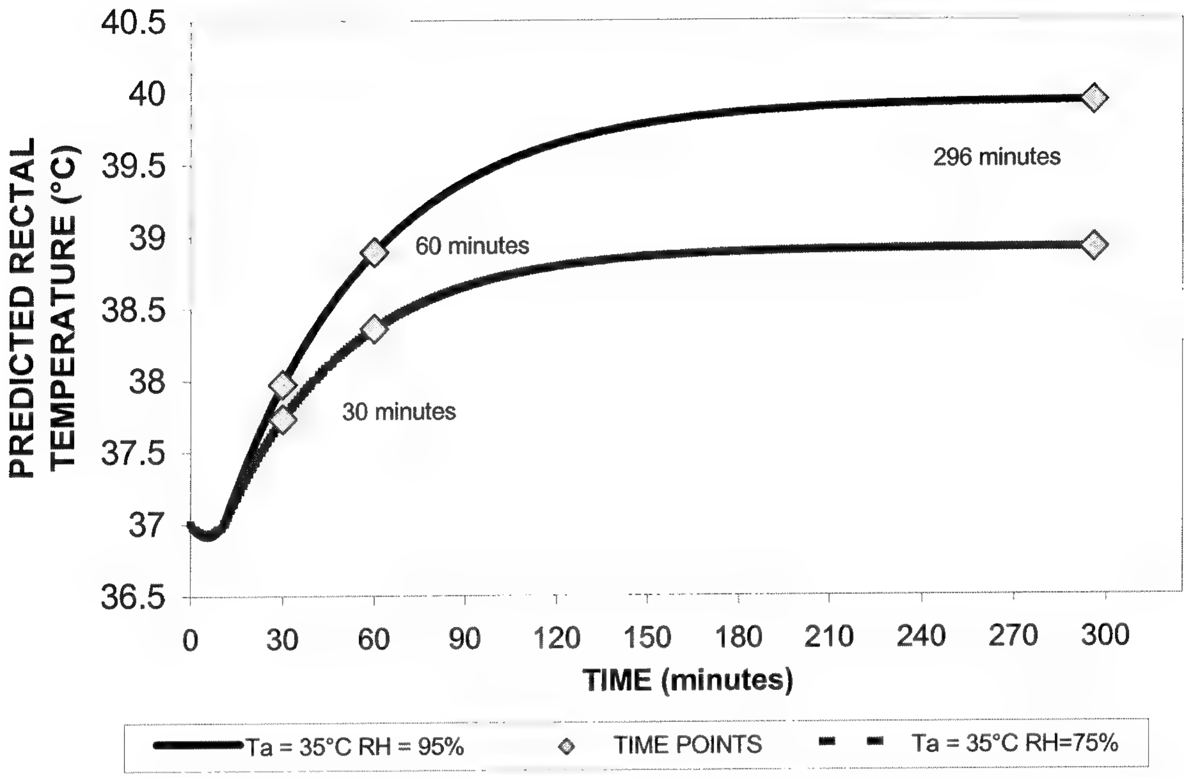
METHODS

The HI was calculated for 71 combinations of T_a and RH that fall within the range of the tables and other restrictions for the adjusted HI (17,18, 22). These restrictions included a minimum RH of 30% and a maximum HI of 135°F. Some NWS tables end at HI=130°F, as that is identified as the maximum hazard level. An important limitation of this study is that the relationship between predicted T_{re} and HI or HD may under-predict actual T_{re} for HI values >135°F. HD values were calculated for the same weather inputs, so there were corresponding values for HI and HD for all 71 conditions. The upper limit for HD within those HI-based restriction, is HD≤56°C. T_a ranged from 26.7°C to 45°C and RH 30% to 100%. Based on Steadman (22,24) a set of constant inputs for height (170 cm), weight (67 kg), clothing (warm-weather BDU, clo=1.3) and metabolic rate (M=320 W) were selected. The height and weight used by Steadman represent the "standard man" of the WWII era. The height and weight of the average male in military service (9) has increased, and Steadman subsequently increased these inputs in a later version of his model (26). However, the standard man values are now a reasonable compromise for a mixed-gender population. Wind speed for an individual was set at 2.5 $m \cdot s^{-1}$. Our values are generally consistent with the inputs identified by Rothfusz (22) for the NWS derivation of HI. The initial T_{re} was 37.0°C. The solar condition was shade – defined as $T_{mrt} = T_a$. An EXCEL version (Microsoft© Corporation, Bellevue, WA) of the USARIEM HSDA was run using each of these input sets. This is equivalent to the laptop version described by Cadarette et al. (2). The important feature of this version of the HSDA is that it allows modification of the k-factor -- a denominator in one calculation that modifies the rate of increase in T_{re}. The k-factor was set at a value of 120. By using a smaller denominator, the model over-predicts T_{re}, thereby creating a safety margin for a healthy military population. Acclimatization was set at 12 days of heat exposure, and the soldiers were normally dehydrated (-1.24%).

Calculation sets (n=71) using those inputs were considered the STANDARD condition. An alternate maximum radiant load condition was defined as $T_{mrt} = T_a + 40°C$ (14). Calculation sets with the alternate value for T_{mrt} were labeled SUN. Calculations were also made with alternate wind speeds of 1.5 $m \cdot s^{-1}$ and 5.0 $m \cdot s^{-1}$, but all other inputs matched the STANDARD input set. Those calculation sets were labeled WIND1.5 and WIND5. The modeling runs for the alternative wind conditions used smaller calculation sets (n=26).

The T_{re} values calculated with the HSDA model at 30 min, 60 min and 296 min (Figure 1) for each weather input set were then copied into worksheets for each of the conditions (STANDARD, SUN, WIND1.5, WIND5). Linear regressions between either HI or HD versus T_{re} were calculated for the STANDARD and SUN conditions. The results for HD suggested (see RESULTS) that a non-linear relationship existed between T_{re} and HD. Based on the pattern of the residuals, simple second-order equations were then developed for the HD relationships. The R^2 values were used as the basis for statistical evaluation. Additional linear regression for HI vs. the WIND1.5 and WIND5 conditions for both STANDARD and SUN were also calculated.

Figure 1. Predicted T_{re} for 35°C, 75% RH and 35°C, 95% RH, shade, highlighted at time=30 min, 60 min and 296 min.



RESULTS

R^2 values for the linear regressions between the thermal indices and T_{re} were $\geq$0.96 for the HI and $\geq$0.90 for HD. Table 1a lists the linear equations and R^2 values for HI and HD in the STANDARD and SUN conditions (Table 1a). Figure 2 illustrates the STANDARD condition 30 min, 60 min and 296 min values for T_{re} plotted against HI. The relationship is clearly linear. Figure 3 shows the relationship between T_{re} and HD. This relationship is apparently curvi-linear, as adding a squared term significantly improves the fit between the indices and the model. The R^2 values for the second-order HD equations improve to $\geq$0.97. Table 1b presents the second order equations that predict T_{re} from HD.

Figure 2. Relationship between Heat Index (HI) and HSDA predicted T_{re} for time =296 min, STANDARD conditions.

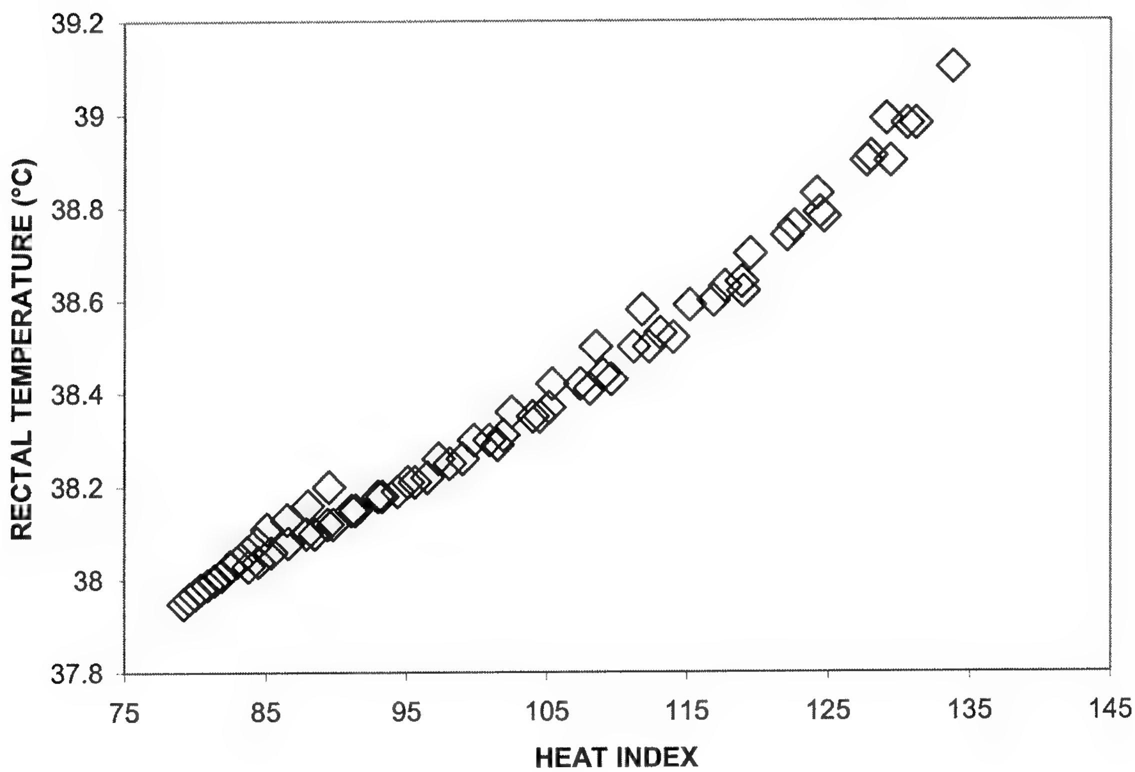


Figure 3. Curvilinear relationship between Humidex (HD) and HSDA predicted T_{re} for time=296 minutes, for STANDARD conditions.

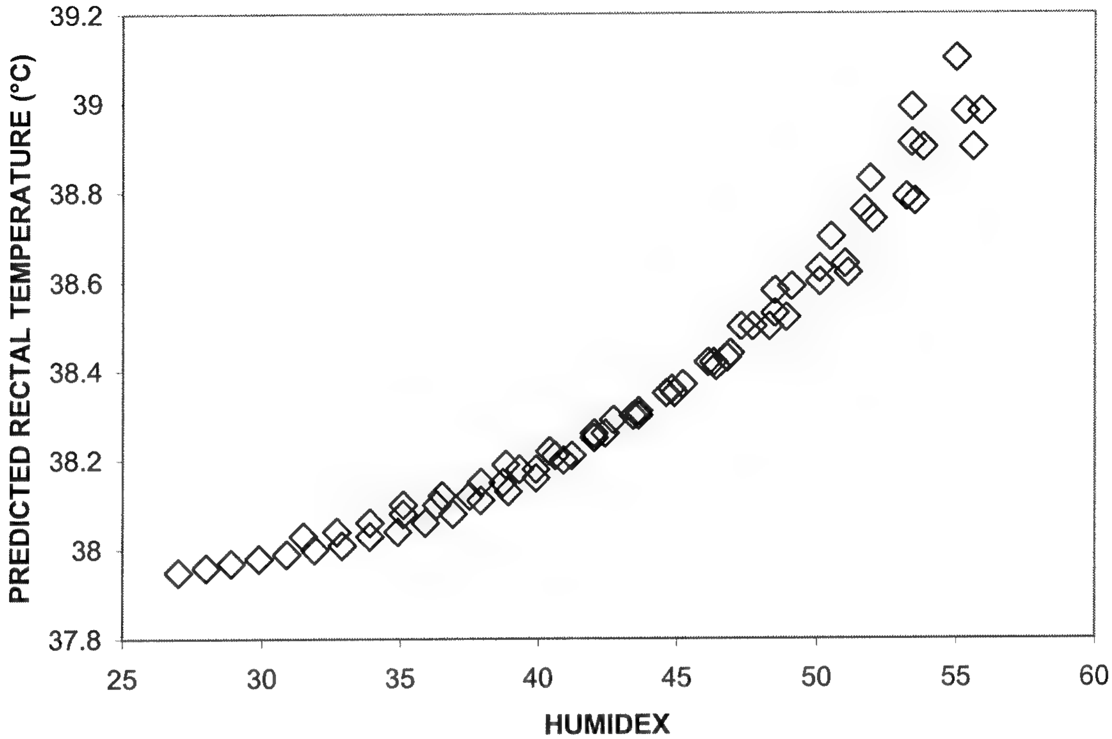


Figure 4. Residuals from Humidex linear regression, STANDARD conditions, time=296 minutes.

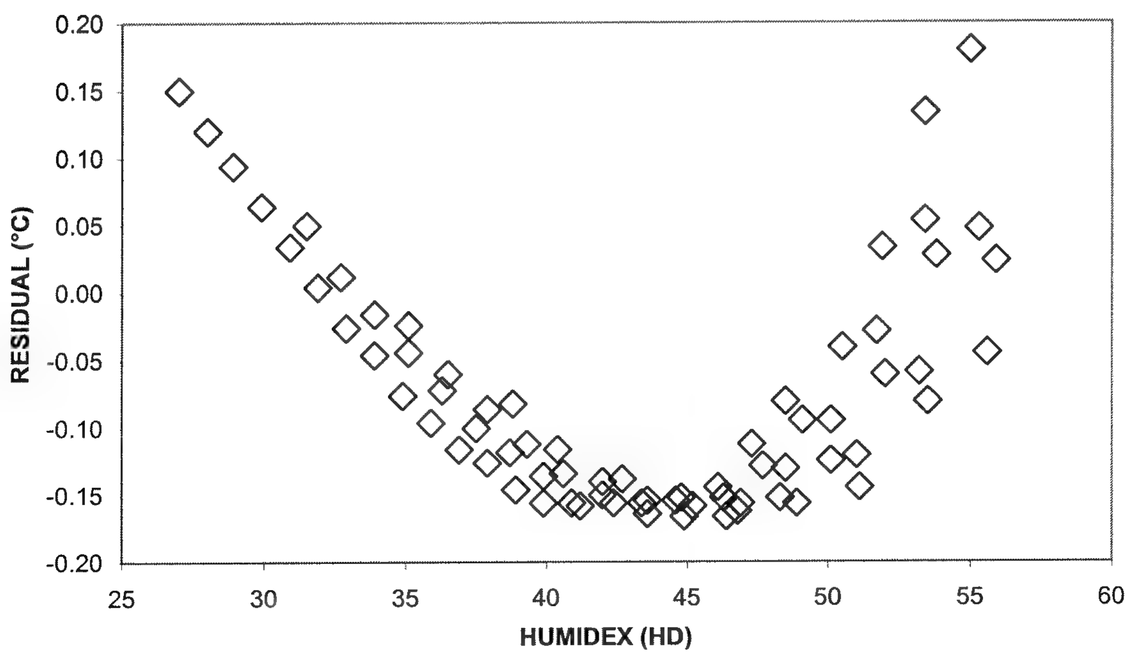


Table 1. Predictive equations for Heat Index (HI) or Humidex (HD) versus HSDA predicted T_{re} (°C).

Table 1a*						
X	TIME	SOLAR	WIND	β_0	β_1	R^2
HI	30	SHADE	2.5	36.939	0.0061	0.99
HI	60	SHADE	2.5	36.773	0.0122	0.98
HI	296	SHADE	2.5	36.436	0.0189	0.98
HI	30	SUN	2.5	36.927	0.0075	0.97
HI	60	SUN	2.5	36.667	0.0158	0.97
HI	296	SUN	2.5	36.026	0.0272	0.96
HD	30	SHADE	2.5	37.027	0.0124	0.94
HD	60	SHADE	2.5	36.950	0.0248	0.93
HD	296	SHADE	2.5	36.863	0.0314	0.93
HD	30	SUN	2.5	37.032	0.0154	0.94
HD	60	SUN	2.5	36.894	0.0323	0.93
HD	296	SUN	2.5	36.434	0.0552	0.90
* $T_{re} = \beta_0 + \beta_1 \bullet X$, HI ≤ 135°F only						

Table 1b**							
X	TIME	SOLAR	WIND	β_0	β_1	β_2	R^2
HD	30	SHADE	2.5	37.635	-0.017	0.00035	0.99
HD	60	SHADE	2.5	38.246	-0.038	0.00075	0.99
HD	296	SHADE	2.5	38.981	0.072	0.00130	0.98
HD	30	SUN	2.5	37.763	-0.020	0.00042	0.98
HD	60	SUN	2.5	38.564	-0.049	0.00096	0.97
HD	296	SUN	2.5	39.805	-0.109	0.00194	0.97
** $T_{re} = \beta_0 + \beta_1 \bullet X + \beta_2 \bullet X^2$, HD≤56°C							

Figure 5 compares the STANDARD shade condition to the SUN condition. Based on the results, the T_{re} for maximum radiant load (SUN) could be estimated from STANDARD predicted values by adding between 0.13°C, 0.27°C, and 0.44°C for t=30 min, t=60 min, and t=300 min, respectively, to the predicted $T_{re.}$ For t=300 min, there is a large range of offset, from 0.24°C to 0.70°C (SD=0.13°C), whereas for the lesser time intervals, the maximum range is >0.2°C. For HD the offsets were 0.13°C, 0.25°C, and 0.45°C for t=30 min, t=60 min, and t=300 min. Figure 6 compares the difference between STANDARD, WIND1.5 and WIND5 conditions at 60 min. Table 2 lists linear equations for the STANDARD, WIND1.5 and WIND5 conditions based on the smaller (N=26) calculation sets. Based on the results, T_{re} for the lower wind speed of 1.5 $m \cdot s^{-1}$ (WIND1.5) could be estimated from STANDARD predicted values by adding an average value of 0.04°C to 0.12°C to the predicted $T_{re.}$ For the higher wind speed of 5.0 $m \cdot s^{-1}$ (WIND5), T_{re} could be estimated from the STANDARD values by subtracting an average of 0.05°C to 0.15°C to the predicted T_{re}. Table 3 summarizes adjustments to HI for non-standard conditions of radiant load and wind speed.

Figure 5. Comparison of predicted T_{re} versus HI for STANDARD and SUN conditions at time=30 min, 60 min, 296 min.

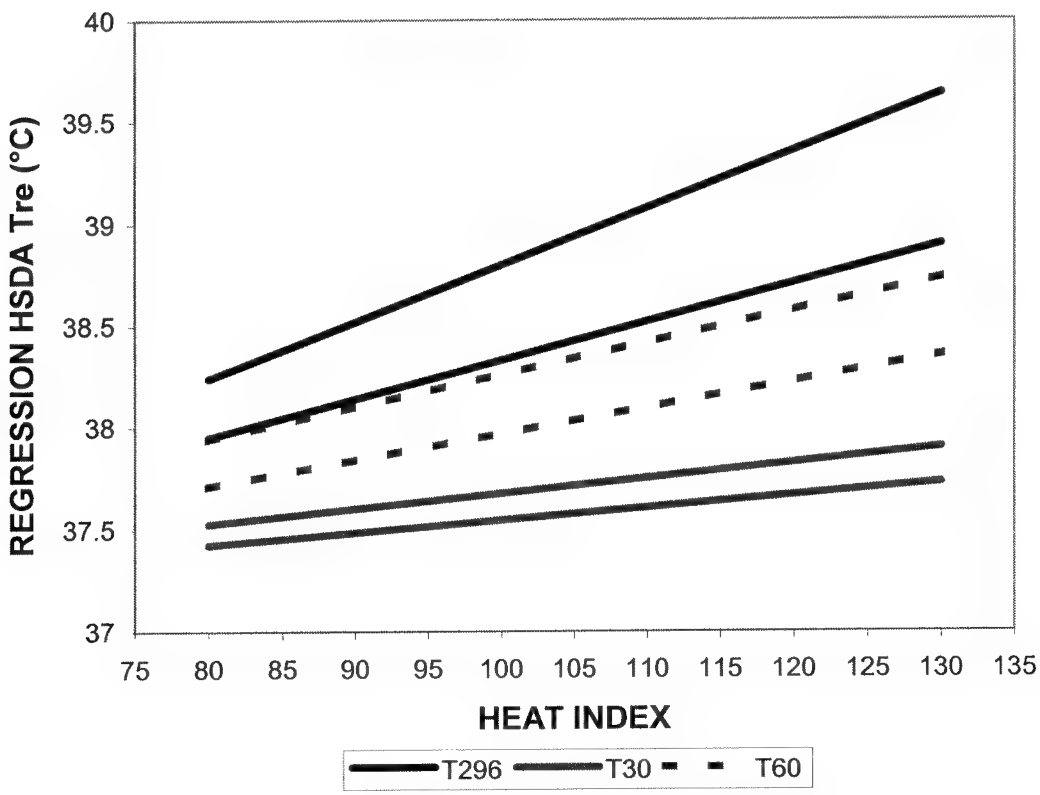


Figure 6. Comparison of predicted T_{re} versus HI for wind speeds of 1.5 $m \cdot s^{-1}$, 2.5 $m \cdot s^{-1}$, and 5.0 $m \cdot s^{-1}$, time = 296 min.

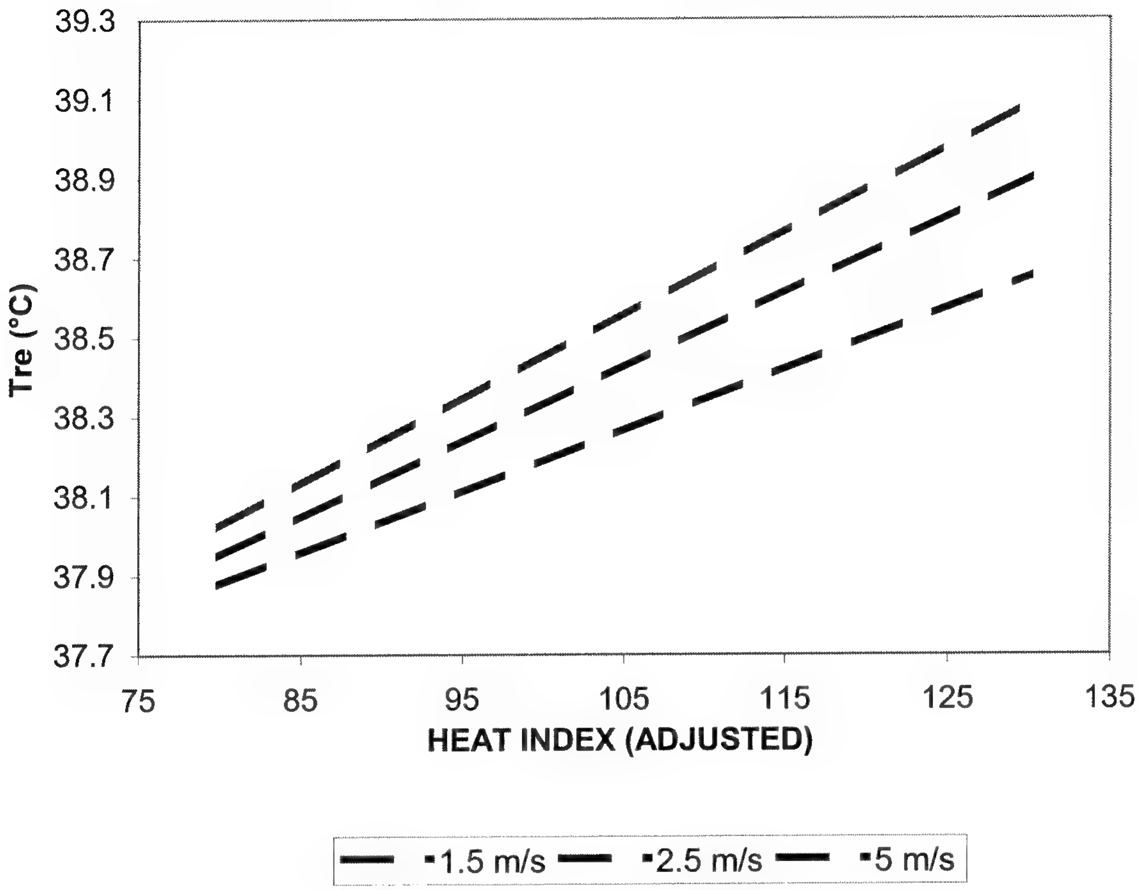


Table 2. Linear regression equations to predict rectal temperature (T_{re}) from the heat index (HI) under varying conditions of wind and radiant load.

Table 2a. Shade (STANDARD) conditions*					
TIME MIN	CONDITION	WIND m/s	SLOPE A	INTERCEPT B	R^2
LOW WIND AND SHADE					
30	STANDARD	1.5	0.0066	36.930	0.98
60	STANDARD	1.5	0.0133	36.735	0.98
300	STANDARD	1.5	0.0213	36.321	0.98
LIGHT WIND AND SHADE					
30	STANDARD	2.5	0.0061	36.937	0.99
60	STANDARD	2.5	0.0122	36.771	0.98
300	STANDARD	2.5	0.0190	36.431	0.98
MODERATE WIND AND SHADE					
30	STANDARD	5	0.0052	36.977	0.99
60	STANDARD	5	0.0103	36.869	0.99
300	STANDARD	5	0.0155	36.639	0.98
Table 2b. Maximum radiant load (SUN) conditions*					
TIME MIN	CONDITION	WIND m/s	SLOPE A	INTERCEPT B	R^2
LOW WIND AND MAXIMUM RADIANT LOAD					
30	SUN	1.5	0.0081	36.924	0.97
60	SUN	1.5	0.0175	36.628	0.97
300	SUN	1.5	0.0317	35.810	0.96
LIGHT WIND AND MAXIMUM RADIANT LOAD					
30	SUN	2.5	0.0075	36.928	0.97
60	SUN	2.5	0.0160	36.661	0.97
300	SUN	2.5	0.0277	35.998	0.96
MODERATE WIND AND MAXIMUM RADIANT LOAD					
30	SUN	5	0.0063	36.980	0.98
60	SUN	5	0.0128	36.825	0.97
300	SUN	5	0.0208	36.428	0.96
*HI ≤ 135°F only					

Table 3. Summary of adjustments for non-standard conditions.

ADJUSTMENT FROM STANDARD 2.5 M•S^{-1} CONDITION FOR WIND		
CHANGE	WIND =1.5 M•S^{-1}	STD→5 M•S^{-1}
TIME=30	0.04	-0.05
TIME=60	0.08	-0.10
TIME=300	0.12	-0.15
CHANGE	SUN→1.5 M•S^{-1}	SUN→5 M•S^{-1}
TIME=30	0.06	-0.07
TIME=60	0.12	-0.16
TIME=300	0.22	-0.27
ADJUSTMENT FROM STANDARD SHADE, 2.5 M•S^{-1} WIND FOR MAXIMUM SUN AND WIND		
CHANGE	STD→SUN, 1.5 M•S^{-1}	STD→SUN, 5 M•S^{-1}
TIME=30	0.19	0.06
TIME=60	0.40	0.12
TIME=300	0.68	0.18
ADJUSTMENT FROM STANDARD SHADE CONDITION FOR MAXIMUM SUN		
CHANGE	STD→SUN	STD →SUN (HD)
TIME=30	0.13	0.14
TIME=60	0.27	0.25
TIME=300	0.44	0.45

DISCUSSION

Which heat index is better? Which model is better? The linear relationship between HI and the predicted rectal temperature is simple and easy to comprehend. An exponential or curvilinear relationship is slightly more complex mathematically. The R^2 values for the predicted T_{re} for the STANDARD and SUN conditions for 3 time periods (30 min, 60 min and 300 min) were averaged. The average R^2 value for HD was 0.979 relative to a value of 0.975 for HI. For all intents, there is no difference. Our methods, based on the model input for HI, were skewed towards HI, but our bias favors HD as opposed to HI. One reason is that HD is a more direct derivation of the impact of Ta and humidity, and is therefore a more basic temperature-humidity index. The HI approach uses a more complex derivation from Steadman's model to arrive at the same basic answer.

Both indices demonstrate that when all other factors are constant, a fairly straightforward relationship exits between T_a, humidity and the potential for evaporative heat loss. Temperature is a good variable to represent the potential for thermal stress in the environment, and humidity determines the evaporative potential of the environment. As evaporative heat loss represents the greatest thermoregulatory potential to compensate for environmental and metabolic heat gain in order to maintain homeostasis, a good correlation might be expected. The actual thermal strain is determined, in large part, by the incompressible heat gain (15). When the thermoregulatory capacity to maintain core temperature within a functional range is exhausted, relatively small increases in net heat storage can result in a significant increase on body temperature and, ultimately, heat injury. Heat indices are a means of expressing a specialized case of convective cooling in a format that is easily communicated and readily comprehended by the general population. Heat indices are virtually analogous to WCT as both types of thermal indices represent a simplification of the dominant thermoregulatory pathway -- evaporation in the heat and convection in the cold. The use of thermal indices may be justified, or at least rationalized, as a means to communicate the potential risk of injury to the general population.

The progression from Steadman's model to an apparent temperature, then back through another model to a core temperature is, to a degree, an exercise in circular logic. In addition, Steadman (25,26) has modified and upgraded his model after the derivation of the HI. Consequently, Steadman has already addressed some of the criticisms of his original model. It is not the intent of this paper to address the relative merits of the Steadman model. Although the USARIEM model shares some characteristics of a heat balance model, the author(s) of this note originate from a different modeling tradition and thus cannot be considered unbiased. The USARIEM modelers were and are more directly involved in the collection of physiological data, use different approaches to characterizing clothing, and utilize other biophysical constructs that Steadman has rejected. The fact that the final results are closely correlated suggests a convergence of heat balance models; or perhaps more appropriately, the "rule" of large systems/numbers – i.e. small errors tend to cancel.

The primary appeal of heat indices is simplicity. The appeal of thermal indices is wide-spread. In addition to the use of HI and HD by the NWS and MSC, respectively, another heat index, Wet Bulb Globe Temperature (WBGT), is the present U.S. military doctrine (3,27). WBGT is also an industrial standard (1,17) for heat injury prevention. All of these indices are categorized as bioclimatic indices (4), as the only variables represent specific elements of the physical environment that alter the rate of heat exchange with the environment. As noted previously, HI and HD are temperature-humidity indices and wind-chill is primarily a temperature and wind index. WBGT combines the 4 basic weather inputs of temperature, humidity, wind and radiation.

Whether the indices are HI, HD or WBGT, only basic meteorological data and simple mathematics are required for their use. When expressed as a simple numerical index or a pseudo-temperature, indices are also easy for the general population to understand. The acceptance of these thermal indices is due, in part, to the fact that the indices can be presented in the format of a simple look-up or survival table.

Unfortunately, the simple outputs also limit the appropriateness of the value to a specific or special case. Both military (3) and industrial (1,17) manuals provide guidance for more specific cases. The best-known military adaptation is to add 8-10°F to WBGT to compensate for Chemical Protective clothing. The ACGIH manual (1) devotes several pages to adaptations for different activities and clothing. In this report, examples of supplemental adjustments to the basic indices or STANDARD condition, include wind speed (WIND1.5, WIND5, SUN) and radiant load. The necessity of using numerous adjustments to the basic indices to adjust for various conditions to a large extent negates the apparent advantage of indices–the inherent simplicity of the basic index.

HSDA v2.1 (23) is an example of a complex mathematical model. HSDA provides more guidance to the user, including maximum work time, recommended work-rest cycles for sustained activity, estimated water requirements, casualty rates and equilibrium T_{re} values for a wide range of clothing and activities. The acceptable levels of risk of heat casualties (Light, Moderate, Heavy) are based on prior studies (7). Other examples of physiologically based thermal models include SCENARIO (10). An advantage of SCENARIO is that it also estimates heart rate, thereby allowing the calculation of the Physiological Strain Index (PSI), an index based on a weighted combination of T_{re} and heart rate that is relatively easy for a non-technical user to comprehend. (16). Models are available in a number of formats. Proposed or existing modeling products from USARIEM include the Pandolf calculator (21), HSDA v. 2.1 (23) on laptop or PDA (Sauter, personal communications, 20 February 03), and the miniature Heat Strain Monitor (HSM), a device that combines an environmental sensor suite that measures T_a, humidity, wind speed and radiant load (13). Weather inputs may be obtained from a variety of sources. Even simple hand-held devices such as the Kestrel© 3000 and 4000 series pocket weather meters (Nielsen-Kellerman Company, Chester, PA) calculate and display HI.

In the electronic information age, complex mathematics is no longer a barrier. Meteorological and physiological inputs must still be limited to the minimum necessary,

with simplifications such as shade, overcast or full sun; clothing menus; mean values for height and weight; and default constants. Outputs must also be simplified and expressed in meaningful ways. However, it is not difficult to convert output into a simple numerical scale. In the example shown in Table 4, the range of acceptable risks lies within a 0-100 index value range, and values outside of that range are clearly hazardous (7,28).

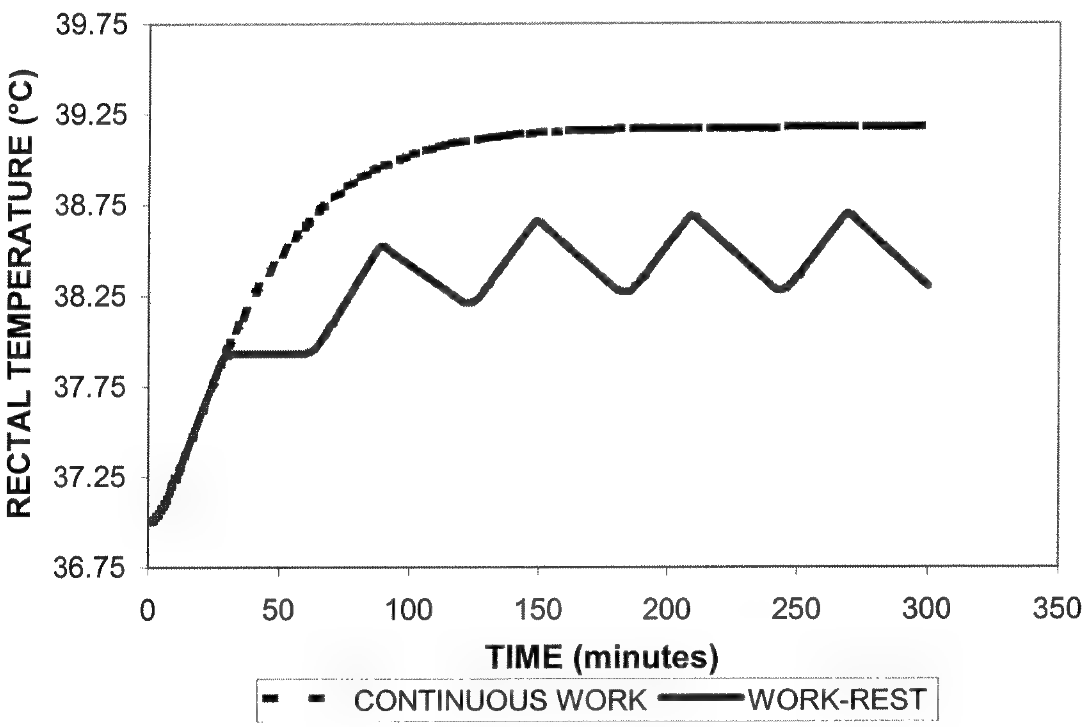
Table 4. The Universal Thermal Index (UTI-X) was generated to demonstrate the principles of indices, rather than as a validated representation of thermal risks.

UNIVERSAL THERMAL INDEX – EXPERIMENTAL (UTI-X)*		
PREDICTED T_{re}	UTI	RISK
<28	-135	DEATH
28	-134	CRITICAL
32	-58	CRITICAL
32.5	-48	DANGER
35	0	DANGER
35.5	10	WARNING
36	19	WARNING
36.5	29	SAFE
37	38	SAFE
37.5	48	SAFE
38	58	SAFE
38.5**	67	WARNING**
39	77	WARNING
39.5	86	DANGER
40	96	DANGER
40.5	105	CRITICAL
41	115	CRITICAL
41.5	125	CRITICAL
42	134	DEATH
* EQUATION UTI = 700 x (T_{re} – 35°C) ÷ 36.5°C [ND]		
** 38.3°C MAY BE BETTER THRESHOLD		

Another limitation of both heat indices is time. The output for HSDA versus HI or HD was presented in this paper at 30 min, 60 min and 300 min of continuous work. Under realistic conditions, an average individual is unlikely to sustain 320 W of activity for much longer than 60 min without a short break. Even a relatively short rest causes core temperature to drop, in effect lowering the restart temperature, but not to a value as low as the initial starting core temperature (Figure 7). A cycle of work-rest will result in a different, lower "equilibrium" temperature. One of the features of the HSDA model is to predict a work-rest cycle that allows a soldier to participate in an activity while remaining below a selected level of thermal strain.

This study was initiated in the context of HI. It was determined that when HI values exceeded 135°F, the predicted T_{re} values no longer fit a linear relationship. Consequently, at higher T_a values, when HI exceeds 135°F, no values for higher humidities were entered. For 45°C, the only RH represented is 30% RH, and for 40°C, between 30% and 50% RH. The corresponding upper limit or HD is 56°C. For combinations of T_a and RH that exceed an HI of 135°, T_{re} may rapidly increase to dangerous levels. An advantage of a physiological model such as HSDA is that these limits do not apply.

Figure 7. Predicted T_{re} from HSDA V2.1 output comparing continuous work at 35°C 50% RH versus recommended work-rest cycle of 28 min work, 32 min rest.



CONCLUSIONS

The results of this study describes a method to estimate T_{re} from the respective heat indices of the U.S. (HI) and Canada (HD). This allows a relatively simple hand-held weather device to provide a physiologically meaningful measure of the thermal environment. However, the results are still subject to the limitations of any thermal index.

The authors prefer the HD over HI as it uses T_{dp} rather than RH and avoids certain assumptions of the Steadman model. HD also more directly represents the physical effects of temperature and humidity. The caveat is that a physiological model based on the heat balance equation, whether Steadman's models or HSDA, is superior to either HI or HD. Heat indices may serve until they are replaced by the UTCI or other thermal models, but the authors strongly endorse physiologically based heat balance models. It is important to emphasize that the results of this study are limited to conditions for HI≤135°F or HD≤56°C. This is a limit associated with the HI and not a limitation of HSDA or other physiological models.

RECOMMENDATIONS

Heat indices should be replaced by thermal models that are based on the physiology and biophysics of heat balance equations.

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